Planetary science

Ices in the Solar System

from I. P. Wright

THE growth of interest in Solar System ices has been generated, in part, by visually spectacular data from the Voyager encounters with the rings and satellites of Jupiter and Saturn. At the same time, substantial advanees have been made with threoretical modelling and observational measurements of dirty ices, long thought to be the primary constituents of cometary nuclei, and there is intensive laboratory study of the physical properties of ice. These and other topics were the subject of a meeting recently held in Nice*.

Water ice is thought to be prevalent in certain satellites of Jupiter and Saturn as well as in comets. E. Whalley (National Research Council, Ottawa) reviewed those properties of water ice (or the 'fundamentals of planetary glaciology' as he preferred to call it) that are pertinent to the study of large icy bodies. The phase diagram of water over temperatures between 0 and −120°C and pressures up to 25 kbar shows nine different polymorphs of ice (called ice I_h, ice II, ice III and so on), some of which are ordered structures, others disordered. A novel ordering transformation identified in ice I_h at low temperatures could possibly occur in an icy Solar System body, catalysed by such substances as ammonia. If so, since the transformation liberates heat, it would have a number of implications for the physical states of planetary bodies.

The water ice deep in the interiors of the satellites of Jupiter and Saturn may be the high-pressure forms, ice VI and VII. J. Poirier (Institut de Physique du Globe de Paris) described the use of a sapphire-anvil squeezer cell to study the laboratory deformation of these forms. By measuring the displacement of markers within the ice crystals it was possible to compute the creep rates of ice as a function of shear stress, temperature and pressure; preliminary measurements of ice VII show it to be extremely hard. Experimental deformation of ice I_h demonstrates that it can exhibit both brittle and ductile behaviour (S. Kirby, US Geological Survey, Menlo Park; W. Durham and H. Heard, Lawrence Livermore National Laboratory). Its brittle character is similar to that of rocks; measurements of ductile strengths, however, indicate that the ice I_h layer on icy Solar System bodies is much weaker than generally thought.

Of relevance to studies of ice accumulation was the report by E. Mayer and R. Pletzer (Universitat Innsbruck, Austria) that the properties of amorphous ice are dependent upon the method of production. In one of their methods, water vapour is leaked through a nozzle into a high-vacuum chamber and deposited as amorphous ice on a cryoplate. The ice, formed in supersonic flow conditions, is found to have a very rough surface; upon warming it shows a number of exothermic peaks. In their alternative method, the water flow is broken up by the introduction of a baffle, whereupon a glass-like ice with a very small surface area is formed. This ice produces only one exothermic peak when warmed. The interesting question that remains is what form of ice might be produced when a solid target travels at high velocity through water vapour, the probable situation in certain Solar System environments.

M. Nicol and co-workers (University of California, Los Angeles) have investigated ice formation in an ammonia–water system at low ammonia concentrations (0–30 per cent) and high pressures (up to 40 kbar), using a diamond-anvil squeezer cell. Microscopy showed that whereas the $NH_3.2H_2O$ phase is characterized by strong anisotropy, smaller refractive index than ice VII and the tendency to form cracks, the $NH_3.H_2O$ phase, which forms at higher pressures, has a refractive index close to that of ice VII and does not form cracks. The outcome of the work has been the production of a preliminary phase diagram for the ammonia–water system. The importance of this system was outlined by S. Miller (University of California, San Diego) who believes that hydrates of ammonia are likely to occur on Uranus and Neptune as well as on the satellites of Jupiter and Saturn.

Accompanying the ammonia hydrates on icy Solar System bodies might be methane hydrate, a substance known to occur on Earth in certain deep-sea sediments. Furthermore, by analogy with the air hydrates found in the terrestrial Antarctic ice cap, it is thought that CO_2 hydrates should be present in the polar regions of Mars (and may also exist in comets). Clathrate hydrates are thus thought to be important and widespread constitutents of Solar System ices and now appear in theoretical models of the physical and chemical states of the saturnian satellite Titan and the neptunian satellite Triton (J. Lunine, Caltech). T. Owen (Stony Brook, State University of New York) demonstrated that the atmospheres of icy bodies are composed of gases which probably result from the dissociation of clathrates. Unfortunately clathrate hydrates have observational characteristics which are indistinguishable from water ice and so, without an actual excursion to one of the icy Solar System bodies, it will not be possible to verify their existence anywhere other than on Earth.

An important constituent of bodies such as Pluto, Titan and Triton is methane ice. Indeed, on Triton there is evidence of islands of solid methane floating on a sea of liquid nitrogen (D. Cruikshank, University of Hawaii). By way of complimenting the observational work, N. Trappeniers (University of Amsterdam) reported that pressures of up to 60 kbar, attained in a diamond-anvil cell, produce evidence of a new phase of methane (phase IV).

All told, the meeting demonstrated that definite progress is being made towards the ultimate goal — a full understanding of the evolution of ices in the Solar System and the construction of consistent models which relate the nature and characteristics of the ices to the materials from which they are formed. It was easy to sense the impatient expectation of many participants for the unique measurements that should come from fly-by missions to Halley's comet when it makes its closest approach to Earth in 1985–6. □

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*"Ices in the Solar System", a NATO-sponsored Advanced Research Workshop, was held in Nice from 16 to 19 January.

100 years ago

AMONG the superabundant "Universities" of the United States Harvard is unquestionably taking its place as a national institution on a par with British establishments which hold a similar designation. The last quarterly *Bulletin* of its proceedings is before us, which has to acknowledge during that short time nine legacies or donations in money, varying from 200 to 100,000 dollars, and amounting to 168,000 dollars. One of these is 10,000 dollars subscribed for the purchase of meteorites, and another is 2000 dollars from the Massachusetts Society for Promoting Agriculture, to assist in the establishment of a veterinary hospital, to which institution also a collection of pathological models is presented.

THE last number of the *Transactions of the Seismological Society of Japan* (Yokohama, 1884) contains various papers on seismology. The first is by Prof. Milne, on earth pulsations; the next is by Mr. Alexander, on the interpretation of a diagram described by a particular form of earthquake instrument. The object of the writer is to calculate not only the maximum velocity, but also the maximum rate at which the velocity changes, "which is a measure of the effect which an earthquake exerts in overturning and fracturing bodies placed on the earth's surface." Prof. Ewing describes the construction of a pendulum which shall be without a tendency to swing when the point from which it is suspended suffers displacement. Mr. Gergens gives a note on ripple-like marks found on the surface of an iron casting supposed to have been shaken while solidifying, which marks are picturesquely described as "a note in a congealed eathquake." The remainder of the volume contains suggestions for new types of seismographs.
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LETTERS TO NATURE

Terrestrial mass extinctions, cometary impacts and the Sun's motion perpendicular to the galactic plane

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Episodes of mass extinctions on the Earth are now strongly suspected to be cyclical[1]. We report here that our analysis of the data of Raup and Sepkoski[1] suggests that the dominant cyclicity in major marine mass extinctions during at least the past 250 Myr is 30 ± 1 Myr, with the standard deviation of an individual episode being ±9 Myr. We find this terrestrial cycle to be strongly correlated with the time needed for the Solar System to oscillate vertically about the plane of the Galaxy, which is 33 ± 3 Myr according to the best current astronomical evidence. It is argued that galactic triggering or forcing of terrestrial biological crises may arise as a result of collisions (or close encounters) of the Solar System with intermediate-sized to large-sized interstellar clouds of gas and dust, which are sufficiently concentrated towards the galactic plane to produce the observed cyclicity and its scatter. Among other consequences, a nearby interstellar cloud would gravitationally perturb the Solar System's family of comets and thereby increase the flux of comets and comet-derived bodies near the Earth, leading to large-body impacts. We find a dominant cyclicity of 31 ± 1 Myr in the observed age distribution of impact craters on Earth, the phase of this cycle agreeing with that shown by the major biological crises. Our galactic hypothesis can thus simultaneously account for the mean interval between major terrestrial crises and for the 50% scatter of the time intervals about their mean value.

Raup and Sepkoski[1] have very recently presented evidence for an approximate cyclicity in marine mass extinctions over the past 250 Myr. Fourier analysis of their data showed a dominant periodicity of 30 Myr, a best-fit curve yielded a cycle of 26 Myr, and a non-parametric test (previously developed independently and somewhat differently in ref. 2) revealed a significant cycle at 26 Myr and an only slightly less significant cycle at 30 Myr. Using less extensive data, Fischer and Arthur[3] had already suggested a 32-Myr periodicity in marine mass extinctions.

Which periodicity, 26 Myr or 30 Myr, should be preferred? Raup and Sepkoski listed all discernible mass extinction peaks that exceeded 2% extinctions on a family level. As they were well aware, however, there are a number of uncertainties in their selection procedure. First, 2% may be too small to be statistically meaningful; Raup[4] elsewhere suggested the use of 10%. Second, there are several minor fluctuations on the time curve of mass extinctions, some of which Raup and Sepkoski selected as true peaks and others they rejected as spurious peaks. Third, as the resolution in time is only one geological stage, other individual minor mass extinction episodes may exist at the substage level. In view of these uncertainties concerning identification and significance, we consider it best to follow Raup[4] and adopt a cutoff of 10% extinctions, while disregarding all the minor inflections on the curve. The large remaining peaks then refer exclusively to the major mass extinction episodes and can be assumed to be completely sampled. They are listed in Table 1 (where the dates have been slightly revised according to ref. 5). Nine dates appear in this table, in contrast to the 12 listed by Raup and Sepkoski.

Intervals of time between successive episodes of major mass extinctions lie in the range 17–53 Myr, with mean time interval 29 Myr. We regard the large (50%) dispersion as physically real, although some of it must be due to uncertainties of the dating. Reasons given below suggest that the dispersion is randomly generated. If, however, a true underlying mean periodicity does exist and no major mass extinction episodes are either missing or redundant, we can unambiguously assign a cycle number to each episode (Table 1). Non-parametric tests (like those in refs 1, 2) are then no longer appropriate. Regression of the episode date on the cycle number by the method of least squares provides an unbiased estimate of the best-fitting mean period, which is found to be 30 ± 1 Myr. If other recently proposed geological time scales are adopted[1], essentially the same mean period emerges. This invariance is not surprising because the central limit theorem ensures that the presence of even rather large random errors in the dates will not significantly affect either the mean time interval or the best-fitting least-squares period.

If the cycle number is left as a free parameter, the best-fitting mean period P derived from a suitable non-parametric method[2], in which the observed times are fitted to a formula of the type $t = t_0 + nP$, is 26 Myr, where t, t_0 and n are an observed time, the most recent epoch and an integer, respectively. This would agree with Raup and Sepkoski's[1] result. However, Raup and Sepkoski have emphasized the approximate nature of any period that can be derived from so few data points. We prefer, in fact, the assignment of the cycle numbers as given above and therefore the period of 30 Myr. There are additional reasons for our preference: first, other kinds of geological data (including 41 dated impact craters) show periods of 30–35 Myr, and, second,

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the larger variance produced with the longer period actually appears to have a natural physical basis, as will be discussed below.

A cyclicity of the specific length and rough regularity shown by the marine mass extinction data is difficult to reconcile with a purely terrestrial triggering mechanism[1,6]. There is also no known solar mechanism that could operate on this long a time scale[7]. A galactic mechanism therefore appears to be the most likely. A number of cycles ranging from 100 to 900 Myr (refs 8–13), are associated with the slow revolution of the Solar System in the plane of the Galaxy about the galactic centre. These cycles, however, are much too long to explain the 30-Myr spacing of the major extinction episodes.

Several authors[13–16] have pointed out that the Solar System also executes a nearly periodic motion perpendicular to the galactic plane (in the z direction). Innanen *et al.*[13] have calculated the Sun's orbit backward in time in a simple, but physically reasonable, model of the Galaxy, and have found the average period for one complete vertical oscillation to be ~67 Myr. They remarked (as had Hatfield and Camp[15]) that a period of this length is similar to the known lengths of the geological periods. The physically meaningful cycles, however, are the dynamical half-periods, $P_{1/2} \approx 33$ Myr (plane crossing to plane crossing). The calculated crossing times of Innanen *et al.* are given in Table 1.

For a slowly moving object like the Sun, the vertical oscillation is essentially a simple harmonic motion governed by the local galactic mass density ρ_0. Innanen *et al.* adopted $\rho_0 = 0.20\ M_\odot$ pc^{-3}, which agrees with recent values of $\rho_0 = 0.14$–$0.21\ M_\odot$ pc^{-3} determined from dynamical studies of nearby stars[17–21]. By using the harmonic relation $P_{1/2}\rho_0^{1/2} = \text{constant}$, we estimate the possible error associated with $P_{1/2} = 33$ Myr as less than ±3 Myr.

The galactic time series in Table 1 can now be compared more rigorously with the terrestrial mass extinction time series. The correlation coefficient computed for the two time series in columns 2 and 3 of Table 1 is very high ($r = 0.996$). Student's t-test for matched pairs[22] (successive time intervals matched between columns 2 and 3) confirms that the mean time interval in the terrestrial series does not differ significantly from the mean time interval, or half-period, of galactovertical oscillation (the probability that $t = 0.91$ with 7 d.f. is $p = 0.40$). No mean phase difference between the two series is detectable, but some individual phase differences are large. Both the tight mean correlation and the significant individual phase differences suggest the following astrophysical model.

Passage of the Sun through the galactic disk involves the Solar System in varying amounts of diffuse interstellar material whose density falls off roughly exponentially above and below the galactic plane,

$$N(z) = N_0 \exp(-|z|/\beta) \quad (1)$$

But the Sun's total vertical trajectory is only ~70 pc (ref. 13), which is less than the vertical scale height $\beta \approx 120$ pc for ordinary interstellar gas and dust clouds[23] ($n = 10^1$–10^2 particles cm^{-3})[24] and less than $\beta \approx 100$ pc for the clouds ejected by supernova explosions[25,26]. Therefore, the Solar System has an almost constant probability of hitting one of these clouds. Because of this, no real periodicity between encounters with either ordinary or supernova-produced clouds could exist. Moreover, significant collisions with supernova ejecta would probably occur less frequently than once every 50 Myr (refs 27–30). Giant molecular clouds (with $n > 10^3$ particles cm^{-3}) are more closely concentrated towards the galactic plane ($\beta \approx 15$ pc assuming $\beta = 2^{-1/2}(z^2)^{1/2})^{31}$, but their encounters with the Sun are expected to occur less frequently than once every few hundred Myr (refs 6, 32, 33).

Unless the giant molecular clouds[6] or other very dense interstellar clouds[24] are much more common than presently thought, the most likely perturbing objects are intermediate-sized clouds. These have $n = 10^2$–10^3 particles cm^{-3}, radius $R = 3$–6 pc and mass $M = 10^3$–$10^4\ M_\odot$ (ref. 24). They seem to be adequately concentrated to the galactic plane, with $\beta \approx 44$ pc (ref. 31). They also appear to be more or less uniformly distributed along the galactic plane[34]; at least they do not show the strong concentration to spiral arms that is characteristic of the largest clouds[35].

To obtain a direct comparison with the vertical distribution of the clouds, the amount of time spent by the Sun at different intervals of height above or below the galactic plane is shown in Table 2; this has been computed by using an analytical integral of the galactovertical orbit equation[36]

$$t(z) = (P_{1/2}/\pi)\sin^{-1}(z/z_{max}) \quad (2)$$

One-third of the Sun's time is spent at $|z| > 60$ pc. This almost guarantees an approximate cyclicity in the long-term rate of collisions with intermediate-sized and large-sized clouds, which will occur preferentially at lower $|z|$ distances, although not always in the galactic plane itself. Using the cloud statistics of Talbot and Newman[24], we estimate about 1 collision per solar passage through the galactic disk. If only tidal (near) encounters with clouds have to be considered, the rate will, of course, be higher.

The one-third of the Sun's time that is spent farthest from the galactic plane is expected to be associated with only 20% of all the collisions and tidal encounters with clouds whose $\beta = 44$ pc, but 33% if $\beta \gg 70$ pc. From the data in Table 1, we find that 11% (1 out of 9 as compared with the expected 2 out of 9) among the major terrestrial extinction episodes actually occur at this unfavoured time. Within the statistical uncertainty, the agreement with our model is good.

Although the Sun at present lies very close to the galactic plane (8 ± 12 pc north), it is passing through a locally poor region of gas and dust[23,27]. It is expected to move out of the region after ~3 Myr, at which time it will again become vulnerable to encounters with the intermediate-sized and large-sized interstellar clouds.

Table 1 Dates (Myr BP) of terrestrial and galactic events

Geological age[1]	Mass extinctions[1]	Galactic plane crossings[13]	Difference	Cycle no.
Middle Miocene	11*	~0	+11	0
Late Eocene	37	31	+6	1
Maastrichtian	66	64	+2	2
Cenomanian	91	100	−9	3
Tithonian	144	135	+9	4
Bajocian	176	166	+10	5
Pliensbachian	193	197	−4	6
Norian	217	227	−10	7
Dzhulfian	245	259	−14	8

The mass extinctions listed here are the major events discussed in the text. Mass extinction dates have been revised after ref. 5. Columns 2 and 3 are not expected to agree in detail, for reasons given in the text.
* The magnitude of this episode is uncertain.

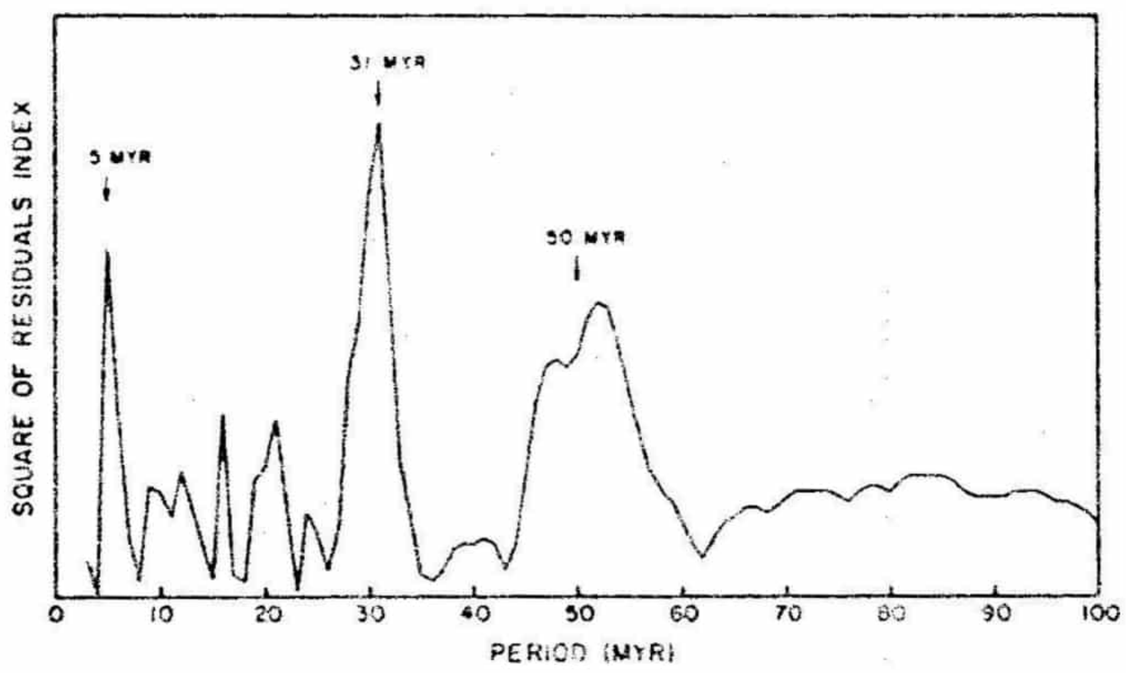

Fig. 1 Terrestrial impact craters: the square of the residuals index (defined in ref. 2) as a measure of the goodness of fit for trial periods that have been fitted to the observed age distribution of 41 craters over the interval $t = 1$–250 Myr (ref. 49).

Table 2 Relative amounts of time spent by the Sun in successive intervals of galactic height

$\lvert z\rvert$ (pc)	z/z_{max}	$\Delta t/P_{1/2}$
0–7	0–0.1	0.06
7–14	0.1–0.2	0.06
14–21	0.2–0.3	0.07
21–28	0.3–0.4	0.07
28–35	0.4–0.5	0.07
35–42	0.5–0.6	0.08
42–49	0.6–0.7	0.08
49–56	0.7–0.8	0.10
56–63	0.8–0.9	0.12
63–70	0.9–1.0	0.29

Table 3 Summary of the mathematical solutions for terrestrial and galactic periodicities

Episodes	Ref.	Most recent epoch (Myr BP)	Cycle (Myr)
Terrestrial			
Mass extinctions (>10%)	1	10±7	30±1
Impacts	49	5±6*	31±1*
Galactic			
Galactic plane crossings	13	~0	33±3*

Terrestrial dates have been revised after ref. 5. Values for the most recent epoch are not significantly different from 0, in view of the size of the associated errors.

* Estimated error.

Two consequences of collisions and tidal encounters with such clouds that may have large ultimate biological impact have been suggested. First, if actual penetration of the cloud occurs, the cloud particle density of $n > 10^2$ cm^{-3} would probably shut off the solar wind at the Earth's distance, as Begelman and Rees[38] have shown. Such a cloud could then directly pollute the Earth's upper atmosphere with hydrogen gas, leading to a variety of possible climatic effects[39–41]. A larger cloud density of $n > 10^3$ cm^{-3} would also raise the Sun's luminosity significantly through gravitational accretion and so would directly affect insolation on the Earth[6,12]. To traverse a cloud of radius 5 pc at a relative speed of 20 km s^{-1} requires 0.5 Myr.

Second, and probably more importantly, even if an actual collision with a cloud does not occur, the cloud's huge mass would gravitationally perturb the Solar System's inner reservoir of comets[42] (as well as the surrounding Oort[43] comet cloud) and so focus a shower of comets on the innermost regions of the Solar System. According to equation (11) of Hills[42], comets having semi-major axes equal to the outer radius ($\sim 2 \times 10^4$ AU) of the inner cometary reservoir will burst into the vicinity of the Earth's orbit if an interstellar cloud of mass 10^3–10^4 $M_\odot$ approaches within 5–15 pc of the Sun. (Smaller interstellar clouds, because of the diffuseness of their mass, could effectively perturb only the Oort comet cloud and therefore would focus only a few comets to small perihelion distances, while significant encounters of the Sun with passing stars would occur only once every 500 Myr.) According to data from Hills, during the calculated 10 Myr lifetime of the expected comet shower[42], probably one large comet and several smaller comets would hit the Earth. Collision of a comet or a comet-derived asteroidal body with the Earth could have severe biological (and other geological) consequences[44–48].

Grieve[49] has recently compiled the ages of all dated Phanerozoic (younger than 600 Myr) impact craters. By applying the above mentioned non-parametric method of time-series analysis[2] to the data in his Table 1 and text and excluding ages given only as upper limits, we find strong signals at periods of 31, 5 and ~50 Myr, as shown in Fig. 1 for the time interval t = 1–250 Myr. These periods are significant at the 1% level, as we have determined by generating and analysing with the same method 5,000 random time series containing the same number of dates. The two periods of 5 and ~50 Myr are artefacts produced by the rounded numbers given for the ages of (mostly older) craters; 61% of the 41 crater ages (t = 1–250 Myr) are divisible by 5, while 22% are divisible by 50. The spectral peak around 31 Myr, however, is consistently high in all of our time-series tests, which include the ranges t = 1–250 Myr (41 craters), t = 30–250 Myr (29 craters), t = 1–600 Myr (62 craters) and t = 250–600 Myr (22 craters).

Some of the craters in the Grieve data set are likely to have been the result of impacts by asteroids of non-cometary origin. However, at present, it is not possible to distinguish between the two types of craters. In any case, non-cometary impacts should be randomly distributed in time and hence should only produce a non-periodic background contribution, like that from the occasional cometary impacts that do not originate from comet showers.

The distribution of the younger crater ages suggests that multiple impacts occurred around 15, 38, 65 and 100 Myr ago, as Seyfert and Sirkin[50] originally proposed. In view of the known dating uncertainties, the dates of these impact episodes are in reasonably good agreement with the dates of the mass extinction episodes of Table 1.

Comet or asteroid impacts have already been inferred from the discovery of geochemical anomalies occurring at the time of the late Cretaceous (66 Myr) extinctions[51,52], which included the disappearance of the dinosaurs, and at the time of the late Eocene (37 Myr) extinctions[53,54]. Several microtektite layers have also been discovered in the 10-Myr interval between 40 and 31 Myr ago[55]. Similar geochemical anomalies and microtektite layers should exist at other relevant boundaries.

If the geological consequences of episodic impacts go beyond immediate effects, as some authors have suggested[44–47], we predict that other kinds of terrestrial data should also show a mean periodicity of ~30 Myr. With similar techniques, a periodicity of 34 Myr has recently been found in the pattern of geomagnetic reversals[56]. Furthermore, we predict that when better extinction data for Palaeozoic times become available, the dominant cycle of major mass extinctions in these earlier times should be ~30 Myr. More speculatively, if one accepts our hypothesis that the basic pacemaker for biological extinctions is the Sun's vertical oscillation through the Galaxy, our line of reasoning can be reversed and we may refine the dynamical half-period of galactovertical motion near the galactic plane by using the terrestrial results summarized in Table 3. We then find $P_{1/2}$ = 30±3 Myr (estimated uncertainty). This seems to support a large local dynamical mass density of $\rho_0 \approx 0.2\ M_\odot$ pc^{-3}. Whether this in turn implies the existence of 'missing matter' in the solar vicinity[19,20] is still uncertain. A last point worth considering for its philosophical implications is that the present mechanism should be operating at roughly the same driving frequency throughout the galactic disk.

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Periodic mass extinctions and the Sun's oscillation about the galactic plane

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Raup and Sepkoski[1] have recently reported evidence for a 26-Myr periodicity in the occurrence of mass extinctions based on a study of marine fossils. The data baseline of 250 Myr suggests events of variable amplitude, with some of the strongest peaks associated with boundaries between major geological periods which have been defined by previous palaeontological studies. In a more limited quantitative study, Fischer and Arthur[2] earlier cited evidence for a 32-Myr period of major extinction events. Hatfield and Camp[3] were among the first to suggest that mass extinctions might be correlated with periodic galactic phenomena, noting intervals of 80–90 Myr between major mass extinctions with an exceptionally strong mass extinction every 225–275 Myr. Here we point out a possible correlation between the 26-Myr extinction period and the Sun's oscillation about the galactic plane.

Due to the disk-like mass distribution of the Galaxy, stars in the disk (including the Sun) experience a restoring force towards the galactic plane which gives rise to harmonic oscillation perpendicular to the galactic plane. Stellar velocity distributions have been used empirically to derive the force law in the galactic plane[4]. Oort calculated a period of the Sun's 'z-oscillation' on the order of 68 Myr and an amplitude of ~100 pc on either side of the midplane of the Galaxy[4,6]. More recent work by Bahcall[7] indicates a slightly stronger force law in the galactic plane than that derived by Oort, suggesting an oscillation period of ~62 Myr. Hatfield and Camp[3] cited earlier work of Trumpler and Weaver[5] which suggested a period of 80 Myr for the oscillation, close to one of the major mass extinction intervals. In addition, they attributed the strong mass extinctions at ~250-Myr intervals to the period of the Sun's revolution around the centre of the Galaxy.

In considering the Sun's harmonic oscillation about the galactic plane, it is important to recognize that the Sun crosses midplane twice in each period, and similarly that it reaches maximum distances from midplane twice each period. Thus any correlation relating to the Sun's position in this oscillation might well involve half the oscillation period, or ~31 Myr. The discrepancy of 5 Myr with the Raup and Sepkoski figure[1] may not be significant in view of the uncertainties associated with establishing each of the periods. In using the Harland time scale for their data set, Raup and Sepkoski recognized the difficulties in establishing an absolute time scale on the basis of a combination of chronostratigraphical sequences and radiometric dating. At the same time, the derivation of the force law in the galactic plane relies on assumptions involving isotropy of the stellar z-velocity distributions. Although isotropy may be indicated by z-velocity distributions of nearby catalogue stars within the local standard of rest (LSR), the LSR could itself possess a z-oscillation which, superposed on the solar oscillation, could yield an effective solar half-oscillation of <31 Myr. We suggest that present uncertainties would easily allow equal periods of ~30 Myr for the geological data as well as for the solar oscillation.

What circumstances could trigger the mass extinctions as function of the Sun's galactic z-position? Passage of the Sun through dense dust clouds located at midplane could in principle provide a perturbing effect on the solar irradiation of Earth, thus initiating climatic changes which would affect the biosphere. However, there is no astronomical evidence for a widespread, flattened dust distribution of sufficient opacity to trigger such an effect with each solar midplane passage. Moreover, data suggest that the Sun is presently only ~8 pc north of the midplane of the Galaxy[9]. As the Sepkoski and Raup analysis indicates that we are presently about midway between mass extinction episodes (the two most recent episodes were ~11 Myr and 38 Myr in the past), this would suggest that the episodes are triggered as the Sun approaches its extreme positions away from the galactic plane. The exceptionally strong extinction event at 65 Myr (the Cretaceous–Tertiary boundary) could have resulted from the superposition of the impact of an asteroid on the longer time scale periodic extinction which was near maximum at the time. This would account for the fact that significant faunal extinctions in excess of those expected from the level of background extinction seem to have been well underway before the deposition of the iridium layer attributed to the impact[10,11].

What other agents of the galactic environment might serve to modulate evolution in the biosphere? Hatfield and Camp suggested that geomagnetic field reversals might be triggered by variations in the galactic magnetic field as the Solar System moves through the galactic plane. At times of null magnetic field strength during the reversals, the increased cosmic ray flux at the Earth's surface could imperil the biosphere. To our knowledge, however, there is no evidence for a periodicity of ~30 Myr in geomagnetic field reversals. Moreover, the galactic magnetic field is six orders of magnitude weaker than the geomagnetic field, and in view of the fact that the magnetic flux associated with the solar wind at Earth is greater than the galactic magnetic flux, it is difficult to understand how the galactic field could perturb the geomagnetic field.

There are two components of the galactic environment which might be expected to undergo substantial changes from the point of view of a star oscillating through a distance comparable to the scale height distribution of interstellar matter. First, electromagnetic radiation in the 2 keV–1 eV range is strongly absorbed by interstellar material which in general obscures sources located more than 1 kpc from the Sun. If a source of radiation is located at midplane at a distance D from the Sun, and if the extinction law can be written

$$\kappa_\nu(z) = \kappa_\nu(0) \exp(-z/L) \qquad (1)$$

where L is the scale height of interstellar matter, the specific intensity of the source as observed from the Sun's present location near midplane ($z = 0$) will be

$$I_\nu(0) = I_{0,\nu} \exp[-\kappa_\nu(0)D] \quad (2)$$

where $I_{0,\nu}$ is the specific intensity at the source. For a position one scale height above midplane ($z = L$), it can be shown that the observed intensity is approximately

$$I_\nu(L) \cong I_\nu(0) \exp[\kappa_\nu(0)D/e] \quad (3)$$

where we have used the condition $D \gg L$. Of special significance is the energy range 2–0.1 keV (soft X rays) where increasing flux is coupled with rapidly increasing optical depth. Using the cross-sections of Brown and Gould[12] and a column density of hydrogen of 6×10^{22} cm^{-2}, characteristic, for example, of the distance to the galactic centre, optical depths are found to increase rapidly for photons with energy <1 keV: $\tau \cong 7$ at 1.5 keV, $\tau \cong 12$ at 1.0 keV, and $\tau \cong 42$ at 0.6 keV. Equation (3) indicates that an optical depth $[\kappa_\nu(0)D]$ of 20, for example, would lead to an enhancement by a factor of ~1,600 in the intensity observed at L in comparison with midplane. The integrated soft X-ray flux from the diffuse galactic X-ray background[13], from discrete sources such as supernova remnants, and from the galactic centre[14] could thus undergo a considerable increase as the Sun approaches a distance comparable to L (~125 pc)[6] from midplane.

A second component of possible significance is the galactic cosmic-ray distribution. The distribution of cosmic rays with height above the galactic plane is unknown. However, if the cosmic rays are confined by the galactic magnetic field, and if the galactic magnetic field is tied to interstellar material, then cosmic rays should have a distribution similar to that of interstellar material. Thus at a scale height above the plane the cosmic-ray flux might be expected to be less than at midplane. Cosmic rays, like soft X rays, play a part in the ionization balance of the upper atmosphere, and in this case one might expect a decrease in the average ionization state as the Sun approaches the extrema of its oscillation. It is not clear whether changes in X-ray flux or changes in cosmic ray flux (which are both absorbed at high altitudes) would dominate.

Because of the harmonic nature of the oscillation, the Solar System would be expected to spend most of its time away from the midplane of the Galaxy. In particular, roughly 4.7 Myr would be spent within 10 pc of each extremum. Changes in cosmic rays in response to variations in solar activity are widely thought to correlate with terrestrial climate cycles[15,16] although the mechanisms for such a relation are not understood. If such correlations are real, it is not unreasonable that long-term changes in these fluxes due to the Sun's z-oscillation could produce significant alterations in the biosphere.

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Are periodic mass extinctions driven by a distant solar companion?

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Raup and Sepkoski[1–3] have recently reported evidence for a 26-Myr cycle in biological mass extinctions which, if real, requires an astronomical explanation. Here we investigate a model in which this extinction cycle is associated with the orbital period of a solar companion star. The required semi-major axis is (a_*), semi-major axis) $\approx 8.8 \times 10^4$ AU = 1.4 light yr. Its highly eccentric orbit ($e_* \geq 0.9$) periodically brings the companion into the dense inner region ($\leq 2 \times 10^4$ AU) of the comet cloud where it perturbs the orbits of large numbers of comets, initiating an intense comet shower[4] in the Solar System which results in several terrestrial impacts over a period of 10^5–10^6 yr. The companion probably has a mass in the black dwarf range of 2×10^{-4} to 7×10^{-2} $M_\odot$, depending on its eccentricity and the density distribution of comets in the inner cloud, and is potentially observable in the infrared.

The putative extinction period, although uncertain by as much as 7×10^6 yr (ref. 1), places the companion roughly near aphelion at the present epoch. The aphelion distance is $Q_* = a_*(1 + e_*) \approx 2a_* \approx 1.8 \times 10^5$ AU, which is near the outer boundary of the Oort comet cloud. Fossil evidence for the extinction cycle extends back 2.4×10^8 yr or 10 companion orbital periods. We consider first the long-term stability of the required orbit against perturbations due to the galactic nucleus, field stars and giant molecular clouds (GMCs).

The time-averaged separation radius is[4] $\langle r_* \rangle = a_*(1 + \frac{1}{2}e_*^2) \approx 1.5a_* \approx 1.3 \times 10^5$ AU, which is compatible with the limit of $\approx 2 \times 10^5$ AU imposed by the galactic field perturbation[5]. The time scale for the dissolution of the solar-companion binary due to stellar encounters is[6]

$$t \sim 1.7 \times 10^{15} \left(\frac{M_\odot + M_*}{a} \right) \text{yr} \quad (1)$$

where the stellar masses are in solar units and the semi-major axis is in AU. Assuming the companion's mass M_* is $\ll M_\odot$ and setting $a = 8.8 \times 10^4$ AU yields $t = 2 \times 10^{10}$ yr. A somewhat shorter time scale is obtained using the mean specific energy transfer rate of $\sim 10^{-13}$ m^2 s^{-3} at 10^5 AU given by Bailey[7].

Although the companion's energy and hence semi-major axis and orbital period are not expected to change significantly over an interval of $\sim 10^9$ yr, the eccentricity and perihelion distance $q_* = a_*(1 - e_*)$ are more easily altered by stellar perturbations. In the context of a model for the density distribution of comets in the inner cloud (discussed below) the maximum perihelion distance is constrained by the required number of shower comets to be $\leq 8.8 \times 10^3$ AU, corresponding to $e_* \geq 0.9$. Beginning with $e_* \approx 1$, the change in perihelion distance in successive orbits is a random walk process with secularly increasing mean perihelia. In an equivalent problem, Fernandez[8] has calculated the mean eccentricity $\bar{e}$ of comet orbits as a function of their semi-major axis (assumed approximately unchanged) for several different time intervals. Beginning with an initial eccentricity $e_0 \approx 1$, Fernandez finds that $\bar{e}$ is essentially unchanged over 10^8 yr independent of the semi-major axis, but significantly changed ($\bar{e} \approx 0.75$) over 10^9 yr for $a \approx 8.8 \times 10^4$ AU. These results depend on the r.m.s. change in angular momentum (or velocity) per orbit and various estimates[7,9,10] differ by as much as an order of magnitude. In view of this uncertainty, we conclude that the companion's eccentricity need not necessarily change appreciably (that is,

$\Delta e \leqslant 0.1$) due to stellar perturbations over 2.4×10^8 yr although a significant decrease would be expected over the age of the Solar System.

The most serious long-term threat to the companion's stability may be perturbations due to the passage of giant molecular clouds of mass $\sim 10^5$–$10^6\ M_\odot$ within a few tens of parsecs of the Sun every $\sim 10^8$ yr (ref. 7), which is comparable to the required lifetime of the present orbit. Comets (and a low-mass companion) at $r \gtrsim 2 \times 10^4$ AU may be disassociated from the Sun by such an encounter. Thus, before the last encounter with a GMC, the present Oort cloud comets (and companion) must have been in closer solar orbits[4,7]. (This assumes that comets and the companion are primordial and have not been captured from interstellar space or from GMCs[11,12].) To have survived this encounter, the companion's semi-major axis must previously have been $< 8.8 \times 10^4$ AU. In connection with this evolutionary scenario, Bahcall and Soneira[13] found that ≈15% of the stars they surveyed were binaries having projected separations of the order of 2×10^4 AU. The apparent absence of significant numbers of binaries with projected separations greater than this safe limit may be explained by encounters with GMCs over the lifetime of the binaries[4]. Our hypothesized solar companion may have been in a similar orbit at $\leqslant 8.8 \times 10^4$ AU during most of the lifetime of the Solar System. The last close encounter with a GMC did not completely disassociate the companion from the Sun but left it in its present eccentric and loosely bound orbit. Alternatively, though less likely, the companion may have been captured during, or subsequent to, the last encounter with a GMC.

The occurrence of a brief but intense comet shower due to the rare (and random) passage of a field star within 2×10^4 AU of the Sun has previously been investigated by Hills[4]. The existence of a dense inner core of comets within this distance has been proposed as a source to replenish comets ejected by encounters with GMCs[4,7,14]. Comets from the dense inner cloud are normally unobserved because distant stellar perturbations are not effective in randomizing their orbits and maintaining a filled loss cone. Hills estimates that the number of comets in the inner cloud may be several orders of magnitude more than the number in the observed Oort halo($\sim 10^{11}$). A solar mass field star passing the Sun with impact parameter b can randomize comets with semi-major axes $a \geqslant b$. Once randomized, the fraction of comets having semi-major axes a and perihelia q is $\approx 2q/a$, if $q \ll a$.

In the numerical example considered by Hills, a $1\ M_\odot$ star of velocity 30 km s^{-1} passes the Sun at $b = 3 \times 10^3$ AU. (The mean interval between such encounters is 5×10^8 yr.) The resulting average comet flux in the inner Solar System ($q \leqslant 2$ AU) was estimated to be 10^4 yr$^{-1} \approx 1$ h^{-1}. The duration of this shower was 7×10^5 yr and the total number of shower comets was $\sim 7 \times 10^9$. The corresponding expected number of terrestrial impacts is $\sim 4 \times 7 \times 10^9\ P_i$ where P_i is the impact probability per perihelion passage for a random long-period Earth-crossing comet which makes on average four perihelion passages[4]. According to Weissman[15], $P_i \sim 2 \times 10^{-9}$ and we could therefore expect ~50 terrestrial impacts from this shower. Of course, the poorly known mass distribution of comets has not been taken into account and the estimated impact number would be accordingly scaled down for massive comets (producing craters ≥ 100 km, say) and scaled up for less massive comets (producing craters ≤ 10 km, say). As noted by Hills, the resulting environmental stress may be expected to significantly affect the distribution of species.

Hills' impulse analysis cannot be taken over directly in the case of a low-mass bound companion. Here we consider the limit of the two-body problem of the scattering of comets by the companion and neglect the relatively small acceleration given the Sun by the companion. The two-body approximation is valid for the scattering of comets which come within the companion's sphere of action radius $d = rM_*^{1/3}$, where r is the Sun–companion separation and M_* is the mass of the companion in solar units. The fraction of comets within this distance which will be scattered into orbits with perihelia $\leqslant q$ is $\approx (2q/r)$. The rate at which these comets are scattered is

$$\dot{N} \approx n\sigma u \left(\frac{2q}{r}\right) \tag{2}$$

Here $n = n(r)$ is the number density of comets, $\sigma = \pi d^2$ is the effective total two-body scattering cross-section and u is the relative velocity between the companion and comet.

The number density of comets can be expressed as $n(r) = C(p)r^{p-4}$ where p is the model index[14]. In the following analysis we adopt the index $p = -1/2$ which is equivalent to the power law model used by Hills[4] and discussed by Bailey[14]. In this model $n(r) \approx 2 \times 10^{17}\ r^{-4.5}$ AU^{-3}, where r is in AU. The relative velocity u is related to the heliocentric circular velocity at r by $u = Uv$, where v is in units of AU yr^{-1} and U is a geometrical factor which depends on (a_*/r), the eccentricities of the companion and comet orbits, and on the relative inclinations of their orbital planes[16]. For all encounter radii and eccentricities of interest, $U \approx 2$. Making these substitutions in equation (2) gives

$$\dot{N} \approx 6.3 \times 10^{19} q M_*^{2/3} r^{-4} \quad \text{comets yr}^{-1} \tag{3}$$

where q and r are in AU.

Integrating equation (3) around an elliptical orbit yields

$$N \approx 3.2 \times 10^{19} q M_*^{2/3} a_*^{-5/2} f(e_*) \quad \text{comets per orbit} \tag{4}$$

where q and a_* are in AU and

$$f(e_*) = \frac{2 + e_*^2}{(1 - e_*^2)^{5/2}} \tag{5}$$

Setting $q = 1$ AU, $a_* = 8.8 \times 10^4$ AU and $N \gtrsim 5 \times 10^5$ gives the required companion mass as a function of eccentricity

$$M_* \gtrsim 2.2 \times 10^2 f(e_*)^{-3/2} \tag{6}$$

The fact that the companion has not yet been identified suggests that its mass may be below the minimum mass of $\approx 0.07\ M_\odot$ required for hydrogen ignition. Inserting this mass into equation (6) gives $e_* \gtrsim 0.9$. A rough lower mass limit can be estimated by imposing the condition that the total mass of comets in the inner cloud be $\leqslant 300\ M_\odot$ or $\leqslant 2 \times 10^{13}$ comets, assuming an average comet mass of 10^{17} g. This limit has recently been inferred by Bailey on the basis of IR observations[17]. In the context of our model for $n(r)$, the total number of comets in the inner cloud is $\approx 1.7 \times 10^{18}\ r_{min}^{-3/2}$, where r_{min} (in AU) is the effective inner boundary of our model cloud. Setting the total number of comets $= 2 \times 10^{13}$ gives $r_{min} \approx 2 \times 10^3$ AU, which is the value suggested by Hills[4]. We now require $q_* \geqslant r_{min}$ or $e_* \leqslant 0.98$. Inserting this eccentricity into equation (6) yields a lower limit of $M_* \gtrsim 2.4 \times 10^{-4}$, which is somewhat less than the mass of Saturn.

The fossil record requires that the duration of the shower be less than a few million years. The strong radial dependency of $\dot{N}$ in our model means that there will be a non-negligible contribution to the shower only near perihelion passage and for all perihelia of interest the characteristic time scale is $\leqslant 10^6$ yr (including four return passages). Other less condensed comet cloud models (that is, $p > 0$) were found to be inconsistent with either the required number of comets or the shower duration time scale for $M_* \leqslant 0.07$.

As previously noted, if the time scale for encouters with GMCs is less than the age of the Solar System the companion must have been in a closer orbit at an earlier epoch. If the earlier orbit was approximately circular at 2×10^4 AU, say, then for $M_* \leqslant 0.07$ and $q = q_{loss} = 15$ AU, the number of comets lost per orbit would have been $\leqslant 10^9$. Assuming that the companion was in this orbit for $\sim 4 \times 10^9$ yr, the total number of comets lost to 15 AU would have been ≤10% of the estimated current number of $\sim 2 \times 10^{13}$ assuming $p = -1/2$. We note that a companion-induced asymmetry in the inner comet cloud might be of interest in connection with the well known anomalous residuals in the motion of Neptune, as discussed recently by Bailey in the context

of a symmetrical comet shell model[14]. The contribution to terrestrial cratering while in this orbit is found from equation (3) with $q = 1$ AU. For $M_* \leq 0.07$, $\dot{N} \leq 66$ comets yr^{-1}, which is not significantly greater than various estimates of the current flux. These crude estimates are model-dependent and are only intended to show that the suggested evolutionary scenario is not necessarily in conflict with the present existence of the inner cloud and the cratering record. A detailed analysis of the evolution of the comet cloud plus companion is beyond the intent of this paper.

As noted above in connection with Hill's analysis, the intrinsic mass distribution of comets is uncertain. Density functions implicitly refer to observable comets of average size since normalization is based on the estimated number of observed long-period comets per year. Here we assume (as did Hills) that the relevant average-size comet has a radius of ~1 km and that the estimate of $\sim 5 \times 10^8$ comets per impact applies to this average comet. Qualitatively, we expect that there are intrinsically many more comets of smaller size. For every 1 km comet that strikes the Earth there will statistically be numerous smaller impacts, as observed in the cratering record. A large 10 km comet will similarly require on average more than $\sim 5 \times 10^8$ comets per impact. We thus anticipate a variation from cycle to cycle in the magnitude of the biological extinctions, depending on the maximum size impact comet as well as variations in the companion's perihelia. However, each cycle could always produce a number of collisions with ≤ 1 km comets. The size and number of comets necessary to significantly perturb the biosphere is uncertain[15], although in the case of the major Cretaceous–Tertiary extinction, estimates suggest that the impacting body or bodies had the equivalent mass of a single ≈ 10 km asteroid or comet[16].

A black dwarf at a distance of $\langle r_* \rangle \approx 1.3 \times 10^5$ AU is potentially observable in the IR (for example, see refs 19–21). Such objects evolve along a vertical Hyashi track in the HR diagram until a final radius of ~0.1 $R_\odot$ is reached, after which they cool radiatively[22]. For example, a dwarf of mass 0.02 $M_\odot$ and age 5×10^9 yr has an absolute 2.2-μm magnitude of 21.3 (refs 19, 22) and a corresponding apparent magnitude of 15.3 at 1.3×10^5 AU. The entire black dwarf mass range could similarly be observed at this distance. A recent search for black dwarfs around nearby stars concluded that these objects must be rare as companions[19]. However, the area searched around the candidate stars was 65×65 arc s or typically $\leq 10^3$ AU and more distant dwarfs (as well as dwarfs at distances ≤ 10 arc s) were not excluded by this search. Although the companion's orbital period, semi-major axis, eccentricity, present distance and mass are all reasonably bracketed by the model, its orbital inclination and aphelion direction are unknown. Nonetheless, the companion is expected to be sufficiently bright in the IR for it to be observable in a full sky survey at the appropriate wavelength. The recent IRAS survey has thus far not found a tenth planet or solar companion, however most of the data analysis is still in progress[23].

The 2.6×10^7 yr extinction period has not as yet been detected in the cratering record (see below) on the Earth or Moon, although there is some evidence for a mean interval of 5×10^7 yr between major impacts[2,3,24]. Finally, we note that the various arguments[20,25–29] invoked to exclude the existence of an hypothesized[30] solar companion at $\sim 10^3$ AU are not applicable to the much more distant low-mass companion considered here.

Since submission of this paper we have received a preprint from Alvarez and Muller[31] reporting the discovery of a periodicity in the terrestrial cratering rate with a period and phase that closely match the extinction period. The cratering period has subsequently been confirmed in an independent analysis by D. Raup and J. Sepkoski (personal communication).

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Extinction of species by periodic comet showers

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A 26-Myr periodicity has recently been seen in the fossil record of extinction in the geological past[1]. At least two of these extinctions are known to be associated with the impact on the Earth of a comet or asteroid with a diameter of a few kilometres (refs 2, 3). We propose that the periodic events are triggered by an unseen companion to the Sun, travelling in a moderately eccentric orbit, which at its closest approach (perihelion) passes through the 'Oort cloud' of comets which surrounds the Sun (ref. 4; see ref. 5 for a review and ref. 6 for a more recent analysis). During each passage this unseen solar companion perturbs the orbits of these comets, sending a large number of them (over 1×10^9) into paths which reach the inner Solar System. Several of these hit the Earth, on average, in the following million years. At present the unseen companion should be approximately at its maximum distance from the Sun, ~2.4 light yr, and it will present no danger to the Earth until approximately AD 15,000,000.

The possibility that major extinctions occurred in a periodic manner was suggested by Fischer and Arthur[7], who believed that the periodicity was driven by a terrestrial mechanism, but it was only the detailed statistical analysis of Raup and Sepkoski[1] that eliminated many questions regarding systematic bias. They weighted each of the 39 customary stratigraphical stages according to the percentage of families in the preceding stage that were extinct in the following stage. A 26-Myr period is evident in the weighted data, and this period was shown by Fourier analysis and Monte Carlo simulation to be statistically significant with a confidence level better than 99%. The boundaries separating stages with large family extinctions are termed 'extinction events', although there is no direct evidence that the extinctions actually occurred at these boundaries. Large excesses of iridium had been found near two of these boundaries by Alvarez *et al.*[2,3], who concluded that the events were triggered by the impact of an asteroid or comet of a few kilometres diameter. Such impacts throw a large amount of dust into the atmosphere, and the extinctions could have been caused by the resulting lack of sunlight, temporary changes in climate, acidification of rain, or by some combination of such factors[8,9].

While impacts on the Earth by asteroids or comets provide plausible explanations for the individual events in which many species are extinguished, it is difficult to explain the precise periodicity of such collisions. Napier and Clube[10] had proposed that periodic catastrophies could be triggered by the capture of comets as the Sun passed through the spiral arms of the Galaxy (for a more recent discussion, see ref. 11). However, it is difficult to reconcile the Napier–Clube model with the relatively stable periodicity discovered by Raup and Sepkoski, in which the last four of the extinction events occurred within 2 Myr of the time predicted by an exact 26-Myr cycle. In addition, as pointed out to us by the Alvarez group, their measurements of isotope ratios of iridium and rhenium imply that the material that hit the Earth was of Solar System origin. The oscillations of the Sun in and out of the plane of the Galaxy have a half-period that roughly matches that required, and one might hypothesize, for example, the presence of an extremely thin layer of debris in the galactic plane that is encountered by the Solar System on each passage. This has the same difficulty as the Napier–Clube model; it predicts impacts with extra-Solar System material. In addition, the Sun is presently near the galactic plane, moving upwards with the relatively high velocity of $\sim 6\,\mathrm{km\,s^{-1}}$. As the last extinction event occurred 11 Myr ago, we are almost half-way between extinctions; thus we have the wrong phase for such an explanation.

If we try to account for the periodicity by postulating an object that orbits the Sun and comes close to the Earth every 26 Myr, perturbations from nearby stars will prevent the orbit from coming into the inner Solar System more than once. An object with this period has a large semi-major axis of ~88,000 AU (where 1 AU is the mean Earth–Sun separation of $1.5\times10^{13}\,\mathrm{cm} = 1.6\times10^{-5}$ light years). If this object passes within 10 AU of the Sun, then its orbit is highly elliptical, with an eccentricity greater than 0.9999. An equivalent way of saying this is to note that the object has very low angular momentum—this not only requires an unlikely fine-tuning of the orbit, but it is also unstable. Within one orbital period the gravitational perturbations of passing stars will cause the orbit to gain enough angular momentum to increase the perihelion distance to more than 100 AU, virtually eliminating its direct effect on the inner Solar System.

However, an unseen solar companion need not come close to the Sun to perturb the cloud of comets that surrounds the Sun at large distances. Oort and others[4–6] showed that there must be about 10^{11} comets in such a cloud with semi-major axis greater than or equal to 30,000 AU. There may be considerably more comets around the Sun than this, as comets with smaller orbits are not significantly perturbed by most passing stars and therefore would usually not be observed on Earth. Hills[12] has estimated the total number of comets to be closer to 10^{13}; even so, the total mass of these comets is probably less than that of Jupiter. The unseen solar companion would perturb such smaller orbits in a periodic manner even if its perihelion were as large as 30,000 AU. With a semi-major axis of 10^5 AU, the orbital eccentricity, e, is 0.7 or greater. Such an orbit requires no 'fine tuning'; in fact, one expects a distribution of eccentricities which uniformly fill phase space to be flat in e^2, with the fraction of orbits having eccentricity greater than e given by[13]

$$N/N_0 = 1 - e^2 \qquad (1)$$

Thus the r.m.s. value of a random distribution of binary orbits has a mean value for the eccentricity of $(0.5)^{1/2} = 0.7$, and this eccentricity is adequate for our orbit. Of course, the larger the eccentricity, the shorter the duration of close passage to the Sun and the shorter will be the periods of maximum perturbation. However, no very tight bounds have been derived from the fossil records on the precise localization in time of the extinction events, so eccentricities as small as 0.7 are still possible. Passing stars will still perturb the orbit of this companion, but they will only gradually change the period and the perihelion. The present orbit, with a semi-major axis of 10^5 AU, will be significantly disturbed and possibly disrupted on a time scale of $\sim 2\times10^9$ yr. (Different authors find slightly different values, between 1 and 4×10^9 yr; refs 13–15. This orbit has probably evolved through a stochastic process, perturbed by random passing stars, from an initial orbit with a shorter period and smaller semi-major axis. Over the past 2×10^8 yr the semi-major axis may have increased by ~10%, and the period by 15% (from Kepler's third law) as the orbital energy decreases linearly on average[13,14]. The uncertainties in the extinction dates are large enough to be compatible with such a drift in period. Once better data are available, it will be useful to test a parabolic fitting to the dates of major extinctions, although purely stochastic 'jitter' from individual stellar passages will always remain in the data even with absolutely perfect dating methods.

What effect will a single passage of a solar companion have on the comets in the Oort cloud? We will follow the detailed analysis of Hills[12] who considered the effects of random (non-periodic) stars passing close to the Sun. Normally the orbits of the comets are distributed isotropically within the cloud, except for orbits that enter the inner Solar System. Orbits which pass close enough to the Sun to be perturbed by Jupiter or Saturn (which have masses of order $10^{-3}\,M_\odot$) are swept out of the Oort cloud, either ejected into hyperbolic orbits or captured into short period (recurrent) orbits. The region in velocity space that is empty because of this effect is known as the 'loss cone', and it contains all the orbits which reach the inner Solar System from the Oort cloud. When a star or other massive object passes through the Oort cloud, the orbits of the comets will be perturbed and the loss cone will begin to fill. Hills showed that the fraction of the loss cone that will be filled is given by:

$$F = \left(\frac{27}{8}\right)\left(\frac{M^2}{M_\odot^2}\right)\left(\frac{a^4}{P^4}\right)\left(\frac{GM_\odot}{qv^2}\right) \qquad (2)$$

where M is the mass of the perturbing star, v is its velocity (assumed by Hills to be $\sim 30\,\mathrm{km\,s^{-1}}$), and P is its distance of closest approach to the Sun; $M_\odot$ is the mass of the Sun, a is the semi-major axis of the comets affected, q is the minimum distance from the Sun that the comet must reach (1 AU if it is to hit the Earth), and G is the gravitational constant. Normally the Earth sits in the quiet 'eye' of the storm of comets, and the comets we see are those that have been perturbed into this normally quiet loss cone region by randomly passing stars.

Hills analysed the particular case of a star with mass similar to that of the Sun passing within 3,000 AU of the Sun, an event that should occur roughly every 500 Myr. For this situation, each of the bracketed terms in equation (2) is of order unity, and the loss cone will be filled. In less than a hundred thousand years a 'shower' of 10^9 comets will reach the inner Solar System. Using the estimates of Weissman[16] and Everhart[17] for the probability of comets hitting the Earth, Hills concluded that for the duration of the shower (10^5–10^6 yr), between 10 and 200 comets will hit the Earth. He mentioned the possibility that such a shower, triggered by the rare passing star that comes within 3,000 AU of the Sun, could be responsible for the Cretaceous–Tertiary extinctions.

One can arrive at a value similar to that of Hills for the number of impacts on the Earth from a comet shower from the following simple considerations. For a comet moving in an ellipse of eccentricity e and semi-major axis a, the distance of closest approach q is given by

$$q \quad a(1-e) \qquad (3)$$

The fraction of comets with e between 1 and e is given by equation (2). Combining these two equations gives

$$N/N_0 = 1 - e^2 = 1 + (a-q)^2/a \approx 2q/a$$

where we have neglected the term $(q/a)^2$. Most of the $N_0 = 10^{13}$ comets in the cloud will be between 10^3 and 10^4 AU. Taking $q = 1$ AU and $a = 10^4$ AU, we find $N = 2\times10^9$ comets showering within the Earth's orbit. (The number of comets that will reach Jupiter's orbit at 5 AU is 10^{10}.) The probability that an individual comet will hit the Earth on a single pass is roughly the projected area of the Earth divided by the area of

its orbit, or 1.6×10^{-9}. Each comet will make, on average, four trips to the inner Solar System[12], and on each trip it has two opportunities to hit the Earth. Taking these values together, we find that the total number of comets expected to hit the Earth is $2\times10^{9}\times1.6\times10^{-9}\times4\times2=25$. Of course this number depends directly on the number of comets in the inner part of the Oort cloud, for which we have no direct evidence.

Using equation (2) we now extrapolate from the case of a random passing star to the situation of a companion to the Sun passing within 30,000 AU at perihelion. The distance of closest approach P is now 10 times larger than for the random passing star case, but the velocity of a companion at this distance is ~0.2 km s^{-1}, 150 times less than the velocity assumed by Hills. Thus, the loss cone will be filled for the same value of a, the comet semi-major axis, of 3,000 AU, and roughly the same number of comets will enter the inner Solar System and hit the Earth, that is, 10–200. Although the impulse approximation assumed by Hills breaks down here, the effect is still of the same order of magnitude. If the mass of the companion is much smaller than 0.1 $M_{\odot}$, the loss cone will not be completely filled and only a few comets will hit the Earth. Of course, our estimates are approximate, and we probably know the number of comets in the Oort cloud only within one or two orders of magnitude. The calculations do show, however, that the model is plausible. Fluctuations in the eccentricity of the orbit (and hence in the perihelion distance) could conceivably account for the slow overall modulation seen in the intensity of the mass extinctions.

The major difficulty with our model is the apparent absence of an obvious companion to the Sun, and the existence of such an object is its most important prediction. We take this prediction seriously largely because of our inability to find any simpler explanation for the periodicity consistent with known facts. Unfortunately, the data are insufficient to allow us to determine where in the sky to look for the as yet unseen solar companion. The known stars nearest to the Sun have been discovered either because of their high apparent brightness, their large proper motion, or their association with other nearby stars. Unfortunately, our proposed companion star is likely to have none of these characteristics. In his review of the known nearby stars[18], van de Kamp explicitly states that the existence of a "distant dwarf star companion (for the Sun) is not excluded".

Harrison[19] considered the possibility of a nearby solar companion affecting apparent pulsar frequencies but his analysis indicated a star too close to the Sun to have the long period we require. (An additional analysis of Harrison's suggestion can be found in ref. 20.) If the solar companion is a black hole or a brown dwarf (a small star which never heated to ignition temperature) then it may be difficult to find. An intense X-ray and γ-ray source, Geminga, has been proposed as an object that may very close to the Sun, although the present limits place it at less than 1,000 light yr[21]. If the companion is a hydrogen-burning M dwarf, its apparent magnitude will be between 4 and 12. There are over 10^{6} stars in the sky within this range, and one of them may be the Sun's companion. The companion will have negligible radial velocity; from our estimate of its present distance (2.4 light yr, calculated assuming that the mass of the star is substantially less than that of the Sun) we expect an annual parallax motion of ±1.4 arc s and a proper motion of 0.01 arc s per year. The large parallax is probably the key to finding the star. The parallax and proper motion are not large enough for the companion to have been spotted in full-sky surveys that use large proper motion to identify nearby stars[22]. It is possible that the companion may not have been identified as such even if it were as bright as 9th magnitude, and a careful search of star catalogues may provide some candidates, but we suspect that it would have been noted years ago unless it is at the faint limit. Analysis of the IRAS data base may yield a candidate brown dwarf. Weakly bound binaries with a semi-major axis of 1.4 light yr are rare in the Galaxy. The observations show a steep drop-off above 0.7 light yr[23] and theoretical arguments (refs 13–15 and I. R. King and J. M. Retterer, in preparation) predict that separations greater than this should occur in fewer than 10^{-3} of star systems. It is possible that the conditions which drive evolution on the Earth are rarer in the Galaxy than had been supposed previously.

The number of comets that arrive in a single shower may be as much as one or two orders of magnitude greater than the number that arrive between showers. This has important implications for our understanding of Solar System physics and evolution. Since the comets fall in from many regions of the Oort cloud, their arrival in the vicinity of the Earth will be spread out over a considerable period of time, perhaps a million years or more. Thus, we do not expect the periodicity in comet impacts to be exact, but instead it should have a slight 'jitter' or variability of about a million years. One should be able to find evidence in the geological record, perhaps by looking for closely spaced iridium layers or by further studies of isotope ratios, that in the average extinction the Earth was hit by more than one comet.

If and when the companion is found, we suggest it be named Nemesis, after the Greek goddess who relentlessly persecutes the excessively rich, proud and powerful. We worry that if the companion is not found, this paper will be our nemesis.

After this paper was submitted, W. Alvarez and R.A.M.[24] found a periodicity in the ages of large impact craters on the Earth, with a period and phase that closely match those of the mass extinctions. In addition, we became aware of evidence in micro-tektite records[25] that there were at least two separate impacts near the Eocene–Oligocene boundary.

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Evidence from crater ages for periodic impacts on the Earth

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Recent evidence has indicated that the impact of a comet or asteroid may have been responsible for mass extinction at the ends of both the Cretaceous[1] and the Eocene[2–4]. Quantitative analysis by Raup and Sepkoski[5] showed that mass extinctions occur with a 26-Myr period, similar to the period seen in qualitative pelagic records by Fischer and Arthur[6]. To account for the possibility of periodic comet showers, Davis *et al.*[7] proposed that such showers could be triggered by an unseen solar companion star as it passes through perihelion on a moderately eccentric orbit. To test a prediction implicit in this model we examined records of large impact craters on the Earth. We report here that most of the craters occur in a 28.4-Myr cycle. Within measurement errors, this period and its phase are the same as those found in the fossil mass extinctions. The probability that such agreement is accidental is 1 in 10^3.

A recent compilation by Grieve[8] lists 88 dated craters for which signs of shock metamorphism suggest probable impact origin. The known craters are located primarily in stable, well-studied regions in North America, Europe, Australia and the USSR. There are no known impact craters on the sea floor. The list shows a strong bias towards recent craters, most of which will probably be removed by erosion in the near future; 12 of the 88 dated craters have ages within the past 5 Myr.

We restricted ourselves to impact craters in roughly the range of ages in which Raup and Sepkoski saw the periodicity: 5–250 Myr BP. The lower limit of 5 Myr was chosen to reduce the bias from the large number of craters surviving from the recent past. In order to be able to see periods as short as 26 Myr, we included only craters whose age uncertainty is ≤20 Myr. Table 1 lists 13 craters that meet this criterion. There have been some improved measurements since Grieve's compilation, and some older ages need to be revised on the basis of new standardized decay constants. After a search of the literature we developed our own revised values for the crater ages and their uncertainties; these are listed in Table 1. To avoid any possibility of bias, however, we confined the bulk of our present analysis to the values given by Grieve rather than our own. We discuss later the effect on our analysis of using the revised numbers instead of Grieve's values.

In Fig. 1*a* a rectangle of unit area has been used to represent each crater having a diameter >10 km. (We will discuss the sensitivity of our analysis to the choice of diameter cutoff later.) The width of the rectangle represents twice the standard deviation error for the age, and overlapping rectangles have been stacked. In Fig. 1*b* the rectangles have been replaced by gaussian distributions, with the r.m.s. for each crater set by the age uncertainty; this plot represents our best statistical representation of the history of impacts on the Earth during the past 250 Myr. A periodicity of about the same frequency and phase as that found in the Raup and Sepkoski analysis is evident, as indicated by the arrows placed at ~28-Myr intervals.

Figure 2 shows the Fourier power spectrum of Fig. 1*b*. (We found no essential difference between the Fourier transforms of Fig. 1*a* and *b*.) In this plot the peak near the frequency 0.035 Myr^{-1} corresponds to a period of 28.4 Myr, with the first maximum at 13 Myr. The arrows in Fig. 1 actually correspond to the frequency and phase found in this Fourier transform. Below we will reconcile our 28.4-Myr period with the 26-Myr period in the palaeontological extinctions.

To understand the statistical significance of the peak in the Fourier power spectrum, we generated Monte Carlo simulations

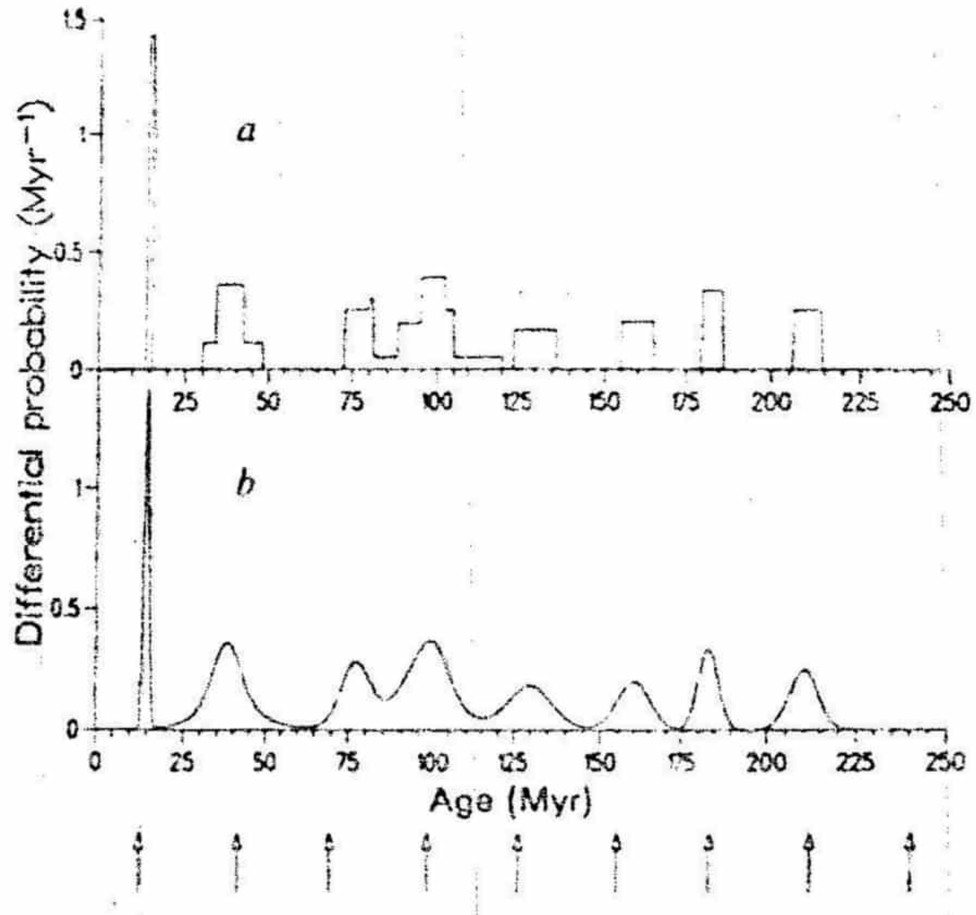

Fig. 1 Impact craters on the Earth having a diameter >10 km and age between 5 and 250 Myr. Only craters having age uncertainties of ≤20 Myr as listed by Grieve[8] have been used. In *a*, each crater is represented by a rectangle of unit area and width equal to twice the age error. In *b*, each crater is represented by the equivalent gaussian curve. The arrows indicate the frequency and phase found from the best fit to the data.

of craters having random ages; 1,000 sets were generated, each containing 11 craters with random ages between 5 and 250 Myr, but with age errors (that is, gaussian widths) identical to and of the same order as those from the real craters. The Fourier transform was calculated for each of the simulated sets; the average of the 1,000 power spectra is indicated by a dotted line in Fig. 2. In each of the 1,000 Fourier power spectra we searched for peaks as high as that seen in the real data; such peaks occurred for frequencies equal to or above 0.035 Myr^{-1} in 8 of the 1,000 randomly generated sets. From this analysis we conclude that the confidence level for the existence of the periodicity is ~99%. Other analyses (for example, finding the number of large peaks in the 1,000 Monte Carlo sets having periods within 2 Myr of the 26-Myr period of Raup and Sepkoski; analysis of the statistics of the peaks; χ^2 calculations; simulations with craters weighted according to diameter) gave confidence levels in the range 97–99.5%. If we take into account the agreement of our periodicity not only in frequency but also in phase with the extinction events of Raup and Sepkoski, we calculate that our confidence level is closer to 99.9%; that is, the probability of random craters giving a signal as large as the one we see, agreeing within 2 Myr in period and 2 Myr in phase.

Figure 3 shows another way of displaying the periodicity (suggested by S. Perlmutter): for every pair of craters in our list of 11 large craters, the difference in their ages was plotted as a gaussian with the two errors combined in quadrature; these gaussians were then superimposed. Peaks are evident in this plot for differences of 28.4 Myr and all multiples thereof.

To estimate the accuracy of our frequency and phase determination, we performed a Monte Carlo generation of 20 sets of craters in each of which the 11 craters were initially forced to occur at precisely 28-Myr intervals, and then randomly 'jittered' (using gaussian statistics) according to the uncertainties in the real crater data. The Fourier transform was then taken, and a best-fit frequency and phase determined. From these simulations we estimate the uncertainty in our period to be ~±1 Myr, and the uncertainty in the time of the first maximum to be ±2 Myr.

The age of the first crater maximum, 13±2 Myr, is identical with the age of the first 'extinction event' of Raup and Sepkoski. One might worry that our slightly different period (28.4±1 Myr as opposed to 26 Myr) would cause our cycles and theirs to be

Table 1 Impact craters of ≥5 km diameter having ages between 5 and 250 Myr with 1 s.d. age uncertainties of ≤20 Myr

Crater no.	Diameter (km)	Age (Myr)	Revised age†	Ref.	Location
43	10		7 ± 4	15	Karla, USSR
35	20		13 ± 11	10	Haughton, Canada
73 (88*)	24	14.8 ± 0.7			Ries, Germany
60	28	38 ± 4			Mistastin, Labrador
99	8.5	37 ± 2			Wanapitei, Ontario
69	100	39 ± 9			Popigai, Siberia
50	14	77 ± 4	78 ± 2	11	Lappajarvi, Finland
87	25	95 ± 7			Steen River, Alberta
18	25	100 ± 5			Boltysh, Ukraine
52	17	100 ± 20			Logoisk, USSR
56	5	118 ± 2	119 ± 2	14	Mien Lake, Sweden
33	22	130 ± 6	133 ± 6		Gosses Bluff, Australia
74	23	160 ± 5			Rochechouart, France
65	15		185 ± 10	12	Obolon, Ukraine
70	80	183 ± 3			Puchezh-Katunki, USSR
54	70	210 ± 4	214 ± 3	13	Manicouagan, Quebec

The first age given is taken from Grieve[8], and it is the primary one used in the present analysis. An age value was only included if there was an error estimate available. Only those craters in this list that have a diameter of ≥10 km are used in Figs 1–3.

* As these two craters are probably from the same event, we included only the larger one.

† Our own estimates based on current values for decay constants, and on radiometric and palaeontological data in the references cited.

of phase after 100 Myr. However, there are uncertainties in the age determination of the palaeontological boundaries that increase significantly for ages >100 Myr. Figure 4 plots a band representing our 28.4 ± 1 Myr period together with the best estimates for the palaeontological ages and errors, as evaluated by Harland *et al.*[9]. With the possible exception of the Tithonian event, a 28.4-Myr periodicity is a good fit to the extinction events of Raup and Sepkoski. Note that there is a slippage of one cycle between the crater events and the extinction events, so that the Permian–Triassic event is cycle 10 in the extinction sequence and cycle 9 in the crater sequence. The cycle slippage occurs in the 150–200 Myr interval, when there are three minor extinction events (7–15% of the families dying out) but only two predicted. We conclude that the record is not well defined in the region of slippage. This is supported by the fact that when Raup and Sepkoski divided the extinction sequence into two halves, they found that 27–29-Myr periodicities were significant to better than 95% confidence levels in both halves. Fischer and Arthur's qualitative cyclicity record[6] shows one less cycle than ours, with the Permian–Triassic event at cycle 8; again the cycle slippage occurs in the 150–200-Myr region, which is clearly the weakest part of the palaeontological–stratigraphical record. The ages of the extinction events are best determined in the most recent four cycles; this is the period for which we test the agreement in phase between the extinction events and the crater ages.

To test the sensitivity to our chosen cutoffs in age and crater size, we have repeated much of the above analysis for different values of these parameters. We varied the crater diameter cutoff continuously from 0 to 20 km; the 28.4-Myr peak was significant at all these values, and reached its maximum intensity for a 5 km cutoff (20% higher than the peak in Fig. 2). Inclusion of the data below 5 Myr or above 250 Myr did not significantly affect the peak height, but it did increase the background level. We also tried removing craters from our list to test the sensitivity of our analysis to the presence or absence of particular craters. The only crater in our nominal list of 11 which does not contribute to the 28.4-Myr periodicity is Lappajarvi, 77 ± 4 Myr old. When we lowered the diameter threshold, adding craters, we found a second peak in the power spectrum at 0.047 Myr^{-1} (period of 21 Myr). A peak at this frequency is also present in Fig. 2 but with less apparent significance. As our noise estimates had been made for random distributions of craters, to investigate the meaning of this peak we generated Monte–Carlo data sets which had a sequence of craters with a real 21-Myr or 28-Myr

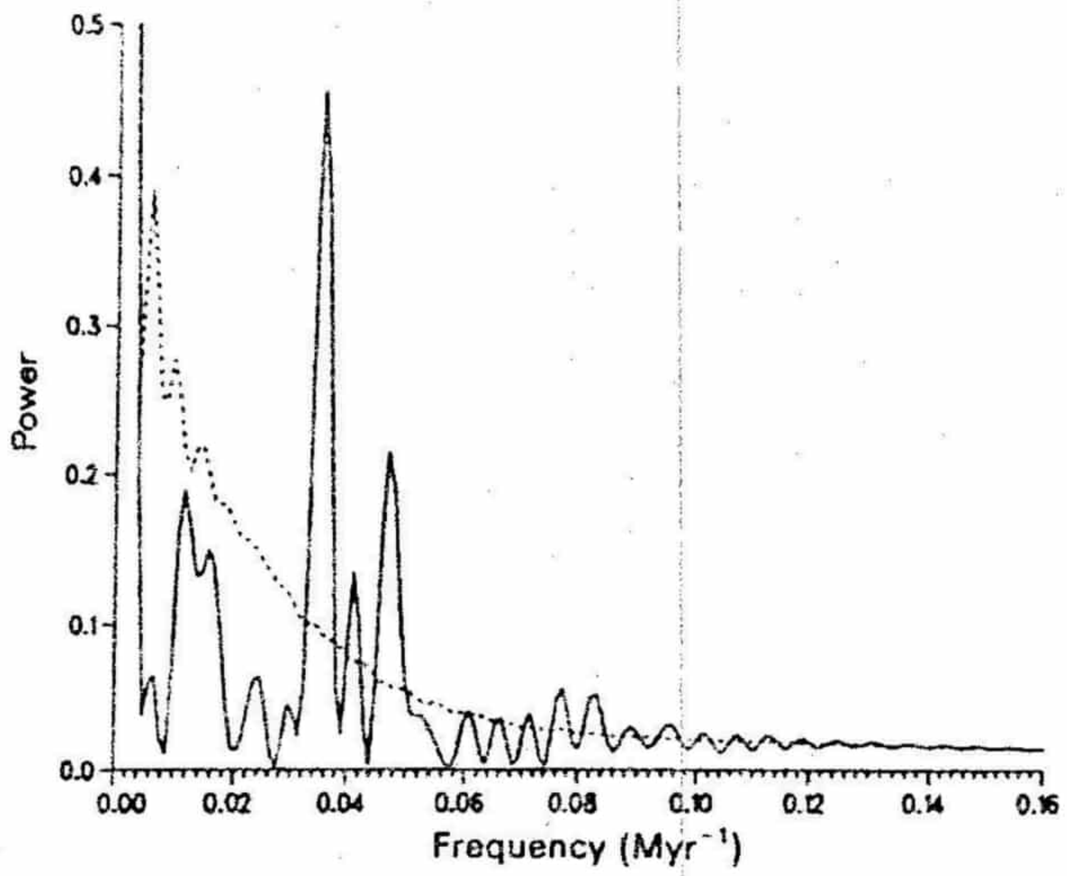

Fig. 2 Fourier power spectrum of Fig. 1*b*. The large peak at 0.035 Myr^{-1} corresponds to a period of 28.4 Myr. The dotted line is a background estimate, taken from the average of 1,000 Monte Carlo-generated data sets, each with a random distribution of crater ages but having the same age uncertainties as the real data.

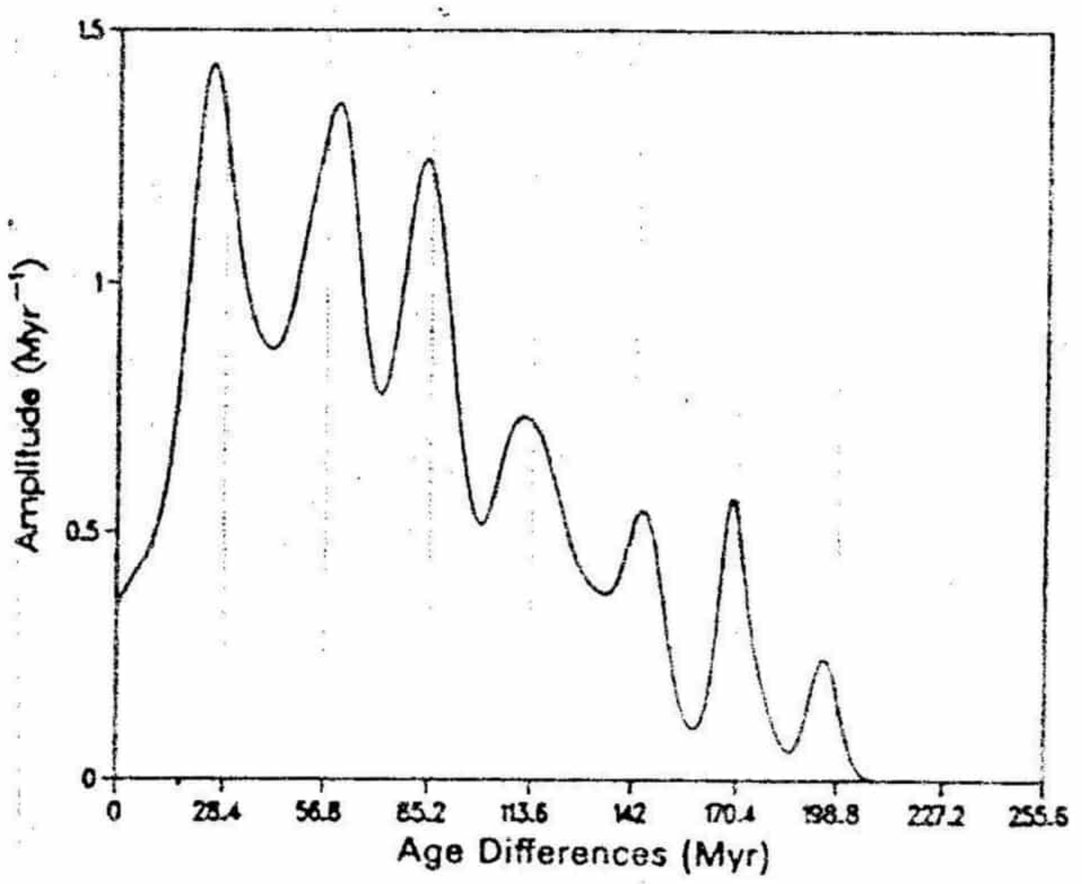

Fig. 3 Distribution of age differences in the crater data. For every possible pair chosen from the 11 craters used in the analysis, the difference in ages was plotted as a gaussian with width equal to the quadratically combined errors for the two ages. The gaussians for all the pairs were then added. The vertical lines are plotted at nominal age differences of 28.4 Myr and multiples thereof.

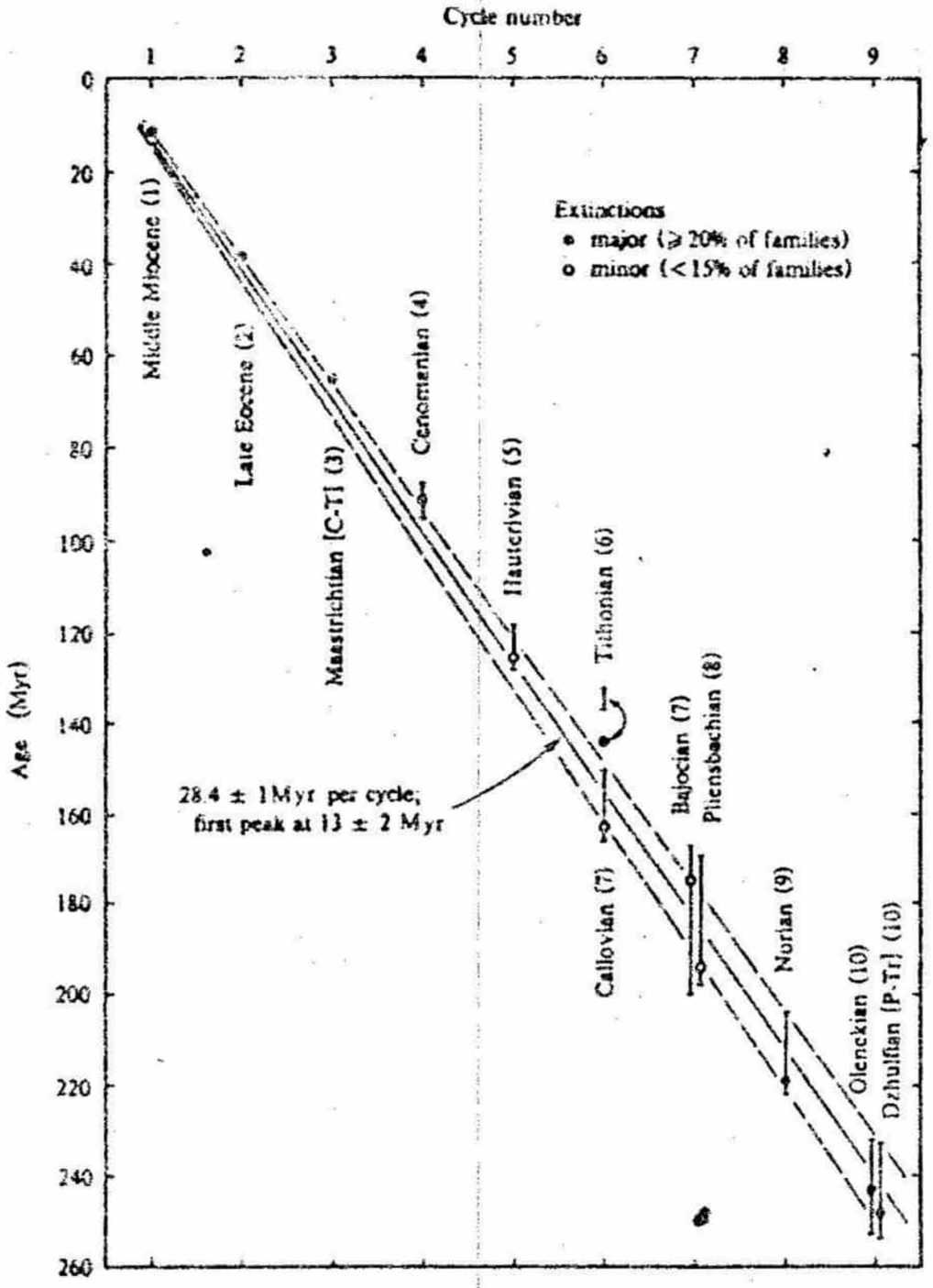

Fig. 4 Comparison of the periodicity found in the crater data with the extinction events from the fossil record. The band represents the periodicity found in the Fourier analysis of the crater data. The data points and confidence limits refer to the 'extinction events' of Raup and Sepkoski[5]. The two largest extinctions occur at the Cretaceous–Tertiary (C–T) and Permian–Triassic (P–Tr) boundaries. The error bars assigned to these events are derived from the review of the time scale by Harland *et al.*[9]. Cycle numbers for extinction events are given in parentheses; slippage of one cycle between the two data sets is discussed in the text. Because of the constraint that palaeontological stages must occur in the proper sequence, model ages[9] sometimes fall outside the range of relevant radiometric data, as in the case of the Tithonian.

periodicity, jittered by the age errors, in addition to a few craters with random ages. We found that in the presence of a real 28-Myr period, a spurious second peak often appeared at 21 Myr, but that in the presence of a real 21-Myr period there was no false 28-Myr peak. Based on these simulations, we believe that there is no significant evidence for a real 21-Myr periodicity. The 21-Myr peak was strongly suppressed when we either increased the crater diameter threshold above 2 km, or weighted the contribution of the craters to the Fourier transform by a factor proportional to their diameters.

As mentioned above, to avoid any possibility of bias in crater selection, we deliberately chose not to reevaluate any of the data in performing our initial analysis, but accepted the compilation of Grieve at face value. We now turn our attention to the revised ages[10–15] in Table 1, which are based on our own extensive search of the literature. Palaeontological dates on lake beds within craters have allowed us to add three new craters to the list: Grieve 43 (10 km diameter, age 7 ± 4 Myr), 35 (20 km diameter, age 13 ± 11 Myr) and 65 (15 km diameter, age 185 ± 10 Myr). The latter two agree reasonably well with our periodicity, which includes 13 Myr and 183 Myr among its cycles. We also list four craters for which there are minor adjustments in the age values or their uncertainties; Grieve 50, 56, 33 and 54. These adjustments make no significant difference to our analysis, except for Grieve 50; this is the 14 km crater at Lappajärvi which, as we noted, does not contribute to the spectrum at 28.4 Myr. With the age estimate tightened from 77 ± 4 to 78 ± 2 Myr, we can definitely exclude it from any cyclic process that has a narrow phase of activity, such as that proposed in the solar companion model[7]. It is vital to obtain smaller errors for the crater ages.

The period and phase of the crater data show strong agreement with those of the palaeontological extinctions, in support of the hypothesis that the extinctions were caused by periodic impact showers. The fact that we find typically one or more craters to associate with each cycle, despite the fact that Grieve's compilation covers less than 10% of the Earth's surface, implies that many impacts occur during each shower. This is corroborated by the discovery of at least two different levels of microtektites near the Eocene–Oligocene boundary[16]. However, given the relatively large crater-age uncertainties, we have, as yet, no indication that the showers have a duration as short as 1–2 Myr. The fact that the periodicity is found primarily among the larger craters suggests that there may be a random background of low-energy impacts in addition to the showers. This is plausible if the shower craters come from comets and the background craters from asteroids. Such background impacts, including an occasional very large one, are inevitable in view of the statistics of modern Apollo asteroids. The long-term cratering rate is considered to be compatible with the current flux of Apollo objects and comets[17–20]. The periodicity of the crater ages may require a revision of this view. Comet velocities are higher than those of the asteroids, and half of the comets (but none of the asteroids) enter the Solar System with retrograde motion leading to head-on impacts. These two factors can increase the impact energies of comets over those of asteroids (assuming equal masses) by an order of magnitude. A modest improvement in the ages measured for a few craters should clarify the nature of the showers.

After this manuscript was submitted, we learned that a solar-companion hypothesis generally similar to that of Davis *et al.*[7] had been independently proposed by Whitmire and Jackson (accompanying paper)[21].

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